Soil-Temperature Regimes--
their characteristics and predictability

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SOIL-TEMPERATURE REGIMES
THEIR CHARACTERISTICS AND PREDICTABILITY

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The temperature of a soil is one of its important properties. Within limits, it controls the possibilities of plant growth and soil formation. Below freezing there is no biotic activity, water no longer moves as a liquid, and unless there is frost heaving, time stands still for the soil. Between temperatures of 32^0 and 42^0 F. root growth of most plants and germination of most seeds is impossible. A horizon as cold as 40^0 F. is a thermal pan to roots of most plants. The soil does not really come to life until its temperature exceeds 42^0 F., and the pace quickens rapidly as the temperature rises above 45^0 F.

Biological processes in the soil are controlled in large measure by soil temperature and moisture. Each plant species has its own temperature requirement. In the Antarctic, for example, there is a microscopic plant that grows only at temperatures below 45^0 F., temperatures at which most other plants are inactive. At the other extreme, germination of seeds of many tropical plants requires a soil temperature of 75^0 F. or more. Plants have one or more soil-temperature requirements that are met by the soils of their native environment. Similarly, soil fauna have temperature requirements for survival. Soil temperature, therefore, has an important influence on biological, chemical, and physical processes in the soil and on the adaptation of introduced plants. Relations of soil temperature to plant growth are not discussed here because they have been reviewed recently (Richards et al. 1952).

As we progress with the national cooperative soil survey and improve our soil classification, we are called on for interpretations to serve more and more uses. We must be able to make quantitative statements about our soils to meet many of these demands. Soil temperature is one basic soil property we should know.

The taxa of our older classifications of soils are partly defined by environment and genesis, giving some control of the variability in soil temperature. Latosols, for example, were confined to the Tropics, Tundra soils to the Arctic regions, Alpine Meadow soils to high elevations and thus to cold climates, and so on. We have been able to restrict the environment of a given soil series so that a soil series of Puerto Rico does not occur in Oregon or Alaska and one in Ohio does not occur in Arizona. But the new soil-classification system that we are developing must be cut loose from the natural landscape if it is to include soils whose properties have been changed by man. In doing this we lose some of the old relationship between soils and their environment, particularly if horizons are very thin, weak, or absent.

Recent alluvium having the same range in texture, mineralogy, reaction, organic matter, and color could occur in Hawaii, Nevada, and Alaska in widely different temperature and moisture regimes. The soil in Alaska would probably be forested and have a thick O horizon. The soil in Nevada might have a cover of scattered shrubs and a vesicular surface crust. The soil in Hawaii would have neither an O horizon nor a vesicular crust. No one would mistake one virgin soil for either of the others. But we need to substitute permanent properties for the distinctive surface horizons that are mixed or destroyed by cultivation.

The environment of a county without mountains is usually uniform enough for differences in genesis due to climate to be disregarded for purposes of a soil survey, but if we classify the soils of the United States or even those of a mountainous county, we cannot disregard the environment entirely. It must be brought into the classification at the phase or some higher level, and soil temperature offers a mechanism to accomplish part of this.

At any one moment, temperature varies from soil horizon to soil horizon. It fluctuates with the hour of the day and with the season of the year, and the fluctuations may be very small or very large according to the environment. Because temperature is so variable or perhaps because it is not preserved in samples, some soil scientists have felt that temperature is not a property of a soil horizon. Most of us who work with soils in limited geographic areas take soil temperature for granted because the temperature of all the soils is about the same. We are all inclined to notice the properties that differ among soils and to focus our attention on them. Yet if one travels, he is impressed by the coldness of soils he examines in high mountains or in boreal forests but not by the coldness of soils in tropical lowlands.

Each pedon has a characteristic temperature regime that can be measured and described. For most practical purposes, the temperature regime can be described by the mean annual soil temperature, the average seasonal fluctuations from that mean, and the mean warm or cold seasonal soil-temperature gradient within the main root zone, the 5- to 100-cm. depth. In this paper, the seasons in the northern hemisphere are winter--December, January, and February; spring--March, April, and May; summer--June, July, and August; autumn--September, October, and November. In temperate regions, we have used

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the mean summer and winter soil-temperature gradients. In tropical regions with pronounced dry seasons, the temperature regime can be better characterized by using the mean dry and wet seasonal soil-temperature gradients.

We have prepared this review of available information to emphasize the kinds of soil-temperature regimes and their relation to environmental factors. Primary emphasis is on soil temperatures in the United States and Puerto Rico, but we have drawn on the literature of many countries for illustrations. The measurements of soil temperature reported have commonly required complex instruments and daily or hourly observations. We will show, however, that most of the relevant parameters can be measured by simple equipment and with little effort.

Data that adequately describe temperature regimes of soils and their relation to environment are scarce because (1) details of the site conditions often are not reported, (2) the observations are not from deep enough layers, (3) the record is not kept throughout the year, or (4) the method of observation results in biased data. The picture we present is as we see it today. Additional data may require some modification in our opinions.

Mean Annual Soil Temperature

Each pedon has a mean annual temperature that is essentially the same in all horizons at all depths in the soil and at depths considerably below the soil. The measured mean annual soil temperature is seldom the same at successive depths at a given location, but the differences are so small that it seems valid and useful to take a single value as the mean annual temperature of a soil. Some representative measurements of the mean annual temperature at various depths in and below selected soils are given in table 1.

Many data show differences in the annual averages of measured temperatures in the first few inches and at depths of more than 20 inches. Some of the data were obtained by daily readings at the same hour, for example, 0800 or at 0800, 1200, and 1800. This method does not give a true average for depths having a daily temperature cycle and thus often introduces a systematic error or bias into the records. Other records are ambiguous because the methods of computing the mean temperature were not given in the references available. The data in table 1 are considered reasonably representative of the most reliable measurements.

Mean annual soil temperature and mean annual air temperature

A comparison of mean annual soil and air temperatures at selected sites in the United States is given in table 2. In computing these averages, we have given the greatest weight to measurements made below the depth of the daily temperature cycle.

IN HUMID TEMPERATE UNITED STATES

In most of the United States, the mean annual air temperature is a consistently good indication of the mean annual soil temperature although the latter is usually a little higher. Examination of the data in table 2 and numerous other data shows that if the mean annual air temperature is 47° F. or higher and

TABLE 2.--Relation of mean annual soil temperature to mean annual air temperature at selected sites in the United States

[Additional information on most of the sites in this table and other sites is given in U.S. Weather Bur. (1961). --- indicates no record]

Location	Depth	Years	Cover	Mean annual soil temperature A	Mean annual air temperature[1] B	A minus B
	In.	No.		° F.	° F.	° F.
Barrow, Alaska[2]--------	0-264	1	Tundra	16.2	[3] 9.8	6.4
Tanana, Alaska[2]--------	12	7	Swamp veg.	32.7	[3] 22.6	10.1
Fairbanks, Alaska[2]-----	1-24	2	---	35.0	[3] 26.0	9.0
Galena, Alaska[2]--------	6-12	6	Moss	37.8	[3] 23.8	14.0
Anchorage, Alaska[2]-----	6-48	5	Bare	39.1	[3] 33.4	5.7
Bozeman, Mont.[2]--------	12-120	5	---	43.3	[4] 42.9	.4
Rainbow Dam, Wis.[2]-----	1-6	5	Grass	44.9	41.0	3.9
Moscow, Idaho[2]---------	0-72	3	---	47.1	[3] 47.6	-0.5
Mount Vernon, Wash.[2]---	6	5	Grass	48.6	[4] 50.6	-2.0
Squaw Butte Expt. Sta., Oreg.[3]--------------	2-24	3	Bunch grass	48.8	46.3	2.5
Ithaca, N.Y.[2]----------	0-96	5	Grass	48.9	[4] 47.1	1.8
Flagstaff, Ariz.[2]------	6	3	Park-pine	49.2	[4] 44.6	4.6
Burlington, Vt.[3]-------	0-10	5	Grass	49.3	44.3	5.0
East Lansing, Mich.[5]---	2-18	2	Bare	50.3	[3] 46.8	3.5
Fort Collins, Colo.[2]---	3-72	41	Grass	50.6	[4] 48.1	2.5
Ames, Iowa[6]-----------	1-72	20	Grass	50.9	[4] 48.9	2.0
Wooster, Ohio[2]--------	3.5	7	Grass	51.4	[4] 50.1	1.3
Coshocton, Ohio[2]-------	5-24	14	Crops	51.9	[4] 52.2	-0.3
Lemont, Ill.[7]---------	0.4-348	3	Grass	52.3	49.1	3.2
Seattle, Wash.[2]--------	0-360	2	Grass	52.5	[3] 51.4	1.1
Prosser, Wash.[2]--------	0.5-12	20	Bare	53.1	[4] 51.0	2.1
Urbana, Ill.[2]---------	0-36	20	Sedge-grass	53.2	[4] 50.9	2.3
Pullman, Wash.[2]--------	1-6	9	Grass	54.6	[4] 52.2	2.4
Conception, Mo.[3]-------	1-6	5	Grass	54.9	[3] 53.0	1.9
Lexington, Ky.[2]--------	3-36	8	---	55.6	[4] 54.9	0.7
Corvallis, Oreg.[3]------	2-40	1	Grass	56.0	52.6	3.4
Union, S.C. (Calhoun)[3]-	1-12	3	Grass	59.5	59.6	-0.1
Auburn, Ala.[2]---------	3-48	1	(Streambank)	65.6	[3] 61.5	4.1
Indio, Calif.[8]--------	12-72	1	Date grove	68.6	71.9	-3.3
Temple, Tex.[2]---------	1-48	7	Grass	70.5	[3] 68.0	2.5
Tifton, Ga.[2]----------	3-6	2	Grass	71.2	[3] 71.3	-0.1
Tucson, Ariz.[2]--------	3-72	1	Bare	73.2	[3] 68.4	4.8

[1] Values are for periods when soil temperature was measured except those from Climate of the States[4], which are normal air temperatures. Air temperatures were not always measured at the exact site of the soil-temperature measurements, and the effects of microclimate are not controlled.
[2] Data from Chang (1958b).
[3] U.S. Weather Bureau climatological data (1895-1963).
[4] Data from U.S. Weather Bureau Climate of the States (1959-1960).
[5] Data from Bouyoucos (1916).
[6] Data from Elford and Shaw (1960).
[7] Data from Carson (1961).
[8] Data from Bliss (1942).

TABLE 1.--Mean annual temperature at various depths in soils and substrata in selected locations[1]

[---indicates no record]

Depth (feet)	Bozeman, Mont.	Seattle, Wash.[2]	Urbana, Ill.	Colombo, Ceylon	Jaipur, India	Irkutsk, U.S.S.R.[2]	Belgrade, Yugoslavia[2]
	° F.	° F.	° F.	° F.	° C.	° C.	° C.
1--------	43.2	---	53.2	85.5	26.9	---	---
2--------	43.4	52.4	53.0	85.7	---	0.7	---
3--------	42.7	---	53.3	85.6	26.9	0.8	12.9
4--------	43.3	51.9	---	85.6	---	1.1	12.8
5--------	43.4	52.2	---	85.7	---	1.5	12.6
10-------	43.9	53.1	---	85.2	27.2	2.0	12.7
20-------	---	52.8	---	---	27.1	2.5	12.6
30-------	---	52.6	---	---	---	---	12.8
50-------	---	---	---	---	---	---	12.9
Mean annual air temperature.	42.9	51.4	50.9	80	25	-2	12.2
Length of soil-temperature records (years).	5	2	20	15	20	18	4

[1] Data from Chang (1958b).
[2] Depths are approximate.

if rainfall is generally adequate in all seasons, level or gently sloping soils have a mean annual temperature about 2° F. higher than the air. Table 2 includes 16 stations that more or less meet these conditions. If we were to estimate the mean annual soil temperature by adding 2° to the measured mean annual air temperature, we would on the average miss the measured soil temperature by only a little more than 1°.

IN COLD CLIMATES

As the mean annual air temperature decreases, the difference between soil and air temperatures tends to increase. At low elevations this is largely, if not entirely, because snow insulates the soil in cold weather. Relations at high elevations are discussed later.

Table 2 shows that the soils of Alaska range from about 6° to 14° F. higher than the air. The mean annual soil temperatures in the U.S.S.R. cited by Golovin (1962) are higher than air temperatures. He cites Shul'gin as showing that the soil is 1° C. warmer than the air in the southern part of European U.S.S.R. and 3.5^o C. warmer in the northern part. In the Amur region of southeastern Siberia, the soils are 3 to 6^oC. (5 to 11° F.) warmer than the air. There the mean annual soil temperatures are reported to range from almost 31° to 40° F. (-0.3^o to 4.3^o C.), and the mean annual air temperature ranges from about 25° to 32° F. These data, shown in table 3, are consistent with the data from Alaska in table 2.

IN HUMID OCEANIC CLIMATES

In contrast to most of the United States, some data from western Europe show soil temperatures to be lower than air temperatures (Chang 1958a, p. 60). This relation has been attributed to the cold rains and to evaporation, but the reduction of solar radiation by the cloud cover may also be an important factor. A similar relation may exist in parts of southern Alaska and in coastal areas of Washington and Oregon, but the only measurements of soil temperature in this region that we have found were made at Seattle, Wash., and Corvallis, Oreg. (table 2). At Seattle, which

TABLE 3.--Relation of average annual soil temperature to air temperature in the Amur region, U.S.S.R.[1]

Place	Average annual temperature		Temperature difference
	Soil at a depth of 20 cm.	Air	
	^{o} C.	^{o} C.	^{o} C.
Ul'minsk Experimental Field------------	1.2	-2.9	4.1
Blagoveshchensk-------------------------	4.3	0.0	4.3
Amur Agricultural Experiment Station----	3.2	-1.3	4.5
Kukhterin Lug---------------------------	-0.3	-4.2	3.9
Komissarovsk grain crop sovkhoz---------	1.6	-1.6	3.2
Belogorsk-------------------------------	3.5	-2.0	5.5
Tarbagatay------------------------------	1.7	-2.8	4.5
Gosh------------------------------------	1.7	-3.7	5.4
Norskiy Sklad---------------------------	2.2	-4.0	6.2
Paykanskiy Sklad------------------------	1.4	-2.8	4.2
Verkhnyaya Tom'-------------------------	0.8	-4.2	5.0

[1] Golovin (1962) p. 216.

has about 32 inches of rain, the soil is 1.1^o F. warmer than the air. At Corvallis in 1961, the soil was 3.4^o warmer than the air. Nevertheless, it is possible that as rain increases, soil temperatures may drop below air temperatures. Both Seattle and Corvallis have very dry sunny summers, thus the climate is not strictly comparable to that of western Europe.

IN DRY CLIMATES

The soil at Tucson, Ariz. (table 2), is about 5° F. warmer than the air. Similar differences have been reported (Smith 1932) at Davis, Calif., where the difference is 7.2^o F. It must be noted that both soils were bare. It must also be pointed out that irrigation can have a drastic effect on soil temperature. For example, an irrigated soil at Vauxhall, Alberta, was 13° F. colder than the air during the summer and 3° colder than the air during the year 1961.[1] An irrigated soil at Indio, Calif., (table 2) was also 3° colder than the air. This is presumably an effect of evaporation.

Mean annual soil temperature and kind of cover

Measurements of the relation of mean annual soil temperature to cover in mid-latitudes are given in table 4.

TABLE 4.--Effect of cover on mean annual soil temperature[1]

Location	Depth	Years	Cover	Mean annual soil temperature A	Mean annual air temperature B	A minus B
	In.	No.		^{o} F.	^{o} F.	^{o} F.
Huntley, Mont.-----	2-60	2	Sod	49.9	47.0	+2.9
Huntley, Mont.-----	2-60	2	Bare	49.2	47.0	+2.2
New Brunswick, N.J.	1-32	6	Sod	52.9	53.0	-0.1
New Brunswick, N.J.	1-8	2	Bare	53.6	52.3	+1.3
Union, S.C.--------	0-72	3	Pine	61.2	61.7	-0.5
Union, S.C.--------	0-12	3	Sod	59.5	59.6	-.1
Union, S.C.--------	0-72	3	Lespedeza	57.2	61.7	-4.5

[1] U.S. Weather Bureau climatological data (1956 and later).

In mid-latitudes it would appear that the kind of cover has at best only a slight influence on the mean annual soil temperature. Other data showing somewhat greater differences have not been included in table 4 because they may have been biased by the time of the temperature readings, which were taken at a shallow depth once a day at a fixed hour.

In high latitudes it is possible that a thick O horizon of needles and moss has a significant effect on the mean annual soil temperature. The O horizon is a permanent layer of insulation; snow is present only in cold weather. An O horizon therefore reduces the relative importance of snow as an insulator. If an O horizon is present, the mean annual soil temperature could be as low as or lower than the mean annual air temperature. The insulating effect of snow cover is discussed more fully later.

[1] Meteorological observations in Canada monthly record, 1961.

Mean annual soil temperature and slope

Few data have been found on the relation of slope gradient and direction to mean annual soil temperature. The mean annual soil and air temperatures of north- and south-facing slopes of 20° (36 percent) were studied under light-shade conditions in a deciduous forest in New Jersey (Cantlon 1953). Over the year the soil at a depth of 4 cm. on the south-facing slope was 4.8^O F. warmer than that on the north-facing slope (fig. 10, p.10). The air 5 cm. above the soil was 6° F. warmer on the south- than on the north-facing slope; 1 meter above the soil it was 1.7^O F. warmer, but at a height of 2 meters there was virtually no difference.

Soil Conservation Service (SCS) staff members measured soil temperatures under grass at Waterford, Calif., at monthly intervals in 1962. The 20- to 30-percent south-facing slope was 6.4^O F. warmer than the 20- to 30-percent north-facing slope. The mean annual soil temperature on the north-facing slope was 66.4^O F. and on the south-facing slope, 72.8^O F.

These observations of soil temperature probably show almost the maximum effect of slope aspect in the United States. The effect of slope depends on sunshine duration. Only in deserts where the soil is bare and sunshine is at a maximum would we expect a greater difference on equivalent slopes. It must be noted that the effect of slope varies with latitude.

Mean annual soil temperature and elevation

Differences in soil temperature related to elevation are relatively complex. With increased elevation, intensity of radiation increases, air temperature decreases, and rainfall and snow may vary erratically.

The mean annual air temperature tends to decrease about 2.7^O F. per 1,000-foot increase in elevation of the earth's surface. The temperature reduction with elevation is greatest in summer when it averages about 3.6^O F. per 1,000 feet; in winter it averages only 2.2^O F. per 1,000 feet.

The difference between air and soil temperature increases with elevation. Carson (1961, p. 46) attributed this to increased radiation, but snow cover often increases and is certainly a factor. We can assume, therefore, that soil temperature may not decrease as much as air temperature.

Mean annual soil temperature and organic-matter content

Bouyoucos (1916) found that there was virtually no difference in the mean annual soil temperature between drained peat and medium- to fine-textured mineral soils at East Lansing, Mich.

Few other comparisons are available between the mean annual temperatures of organic and mineral soils. Records at Flahult, Sweden (Chang 1958b), show that the mean annual temperatures of a wet bog and a well-drained sand are practically identical (fig. 14, p. 12). From these examples it seems that neither ground water nor organic-matter content influences the mean annual soil temperature appreciably.

Mean annual soil temperature and soil color or texture

Bouyoucos (1916) in his studies of the effect of color and texture on the mean annual soil temperature recorded the following mean annual soil temperatures (6-inch depth).

Soil texture	Not covered with sand	Covered with sand
	^{O} F.	^{O} F.
Gravel	51.1	51.9
Sand	51.3	52.0
Loam	49.4	51.5
Clay	50.0	51.9
Peat	49.4	52.5

He concluded that coarse-textured soils are warmer because they hold less water that can evaporate and cool them. After covering all the soils with sand to reduce evaporation, he found no differences in soil temperature. The main conclusion he reached, however, was that color and texture have a very minor effect on the mean annual soil temperature.

Fluctuations of Soil Temperature With Time

The mean annual temperature of a soil is not, of course, a single reading but an average of a series of readings. Near the surface this series may fluctuate from the mean fully as much as air temperature, especially if there is no insulating cover. The fluctuations occur as daily and annual cycles, which in most places are made somewhat irregular by weather events. The fluctuations decrease and are ultimately damped out with increasing depth in the substrata in a zone of constant temperature that is the same as the mean annual temperature.

Short-term temperature fluctuations

DAILY FLUCTUATIONS

Daily changes in air temperature have a significant effect on surface-soil horizons to a depth of about 20 inches (50 cm.). The fluctuations may be very large, particularly in soils of dry climates where the daily range in temperature of the upper inch may approach 100° F. Sutton (1953) has pointed out that for middle and high latitudes a representative daily range on a sunny summer day is 25° C. (45° F.). At the other extreme under melting snow the surface temperature may be constant throughout the day.

Daily soil-temperature fluctuations are affected by clouds, vegetation, length of day, soil color, soil

slope, soil moisture, air circulation near the ground, and the temperature of any rain that falls. Moisture can be exceedingly important in reducing fluctuations in soil temperature. The specific heat of water is roughly five times that of soil minerals and twice that of dry organic matter. The specific heat of water is roughly four times that of dry surface horizons, and the specific heat of medium-textured surface horizons at field capacity is roughly twice that at the wilting point. Water increases thermal conductivity, and it can also absorb or liberate heat by thawing and freezing or by evaporating and condensing. All effects reduce fluctuations at the surface.

To illustrate the daily temperature fluctuations that can be expected over much of the United States, two examples from the more extensive foreign literature are reproduced. Figure 1, taken from Chang (1958a), shows the change in temperature with depth at various hours during a summer day at Griffith, Australia. Between 0600 and 1200, the surface temperature is rising but the temperature at 24 cm. is falling. The daily maximum at the surface comes at or before 1500, but the maximum at 24 cm. is not reached until between 2000 and 2200.

Figure 2 (Rode 1955, after Homen 1897) shows the daily temperature cycle in a soil in Finland by lines connecting points of equal temperature. The hours of the day for 2 days are shown by vertical lines. To determine temperatures at any hour, locate the hour and read down. To determine the temperature changes over time at any given depth, locate the depth and read across. At a 30-cm. depth on August 12, for example, the soil temperature fell until about 1100; from 1100 to 2200 the temperature rose about 2° C. The temperature at a 10-cm. depth fluctuated between about 14° C. and 21.5° C. on August 12 and between 14° C. and 19° C. on August 13. The dashed lines indicate the boundaries between the heating and cooling
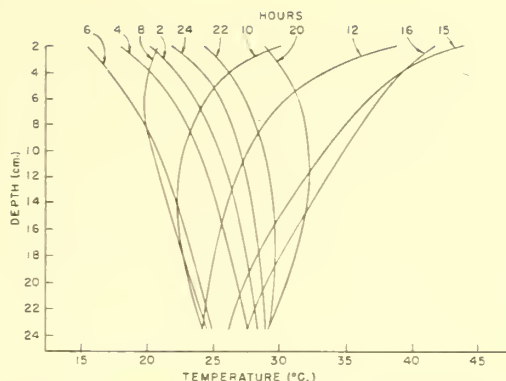

Figure 1.--Variation of soil temperature with depth at each of several hours during the course of a summer day at Griffith, Australia (from Chang 1958a).

cycles. At a 50-cm. depth, the fluctuation is only a fraction of a degree and the time lag is about 18 hours. At 60 to 70 cm. the cycle disappears.

FLUCTUATIONS DUE TO CHANGES IN WEATHER

Soil temperatures also fluctuate with weather that brings below-average or above-average air temperatures for short periods. The weather fluctuations extend to a greater depth than the diurnal cycle. Weather changes tend to last a few days to a week in most of the United States but, like weather patterns in general, occur at irregular intervals.

Figure 3, after Carson (1961), shows that the soil temperature at a depth of 1 cm. is closely related to insolation and air temperature. Changes in soil temperature at this depth reflect hourly variations in insolation (April 16 and 17). Temperatures at 1 cm. were also affected by the warm air mass that moved in on April 20. The soil temperature at a depth of 50 cm.
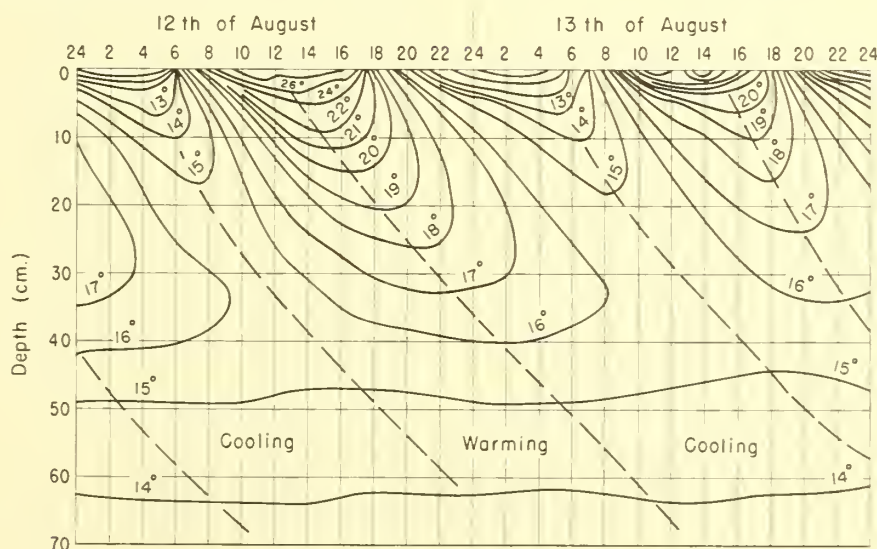

Figure 2.--Daily temperature waves (° C.) in a sandy heath soil at Mustiala, Finland (from Rode 1955, after Homen 1897).
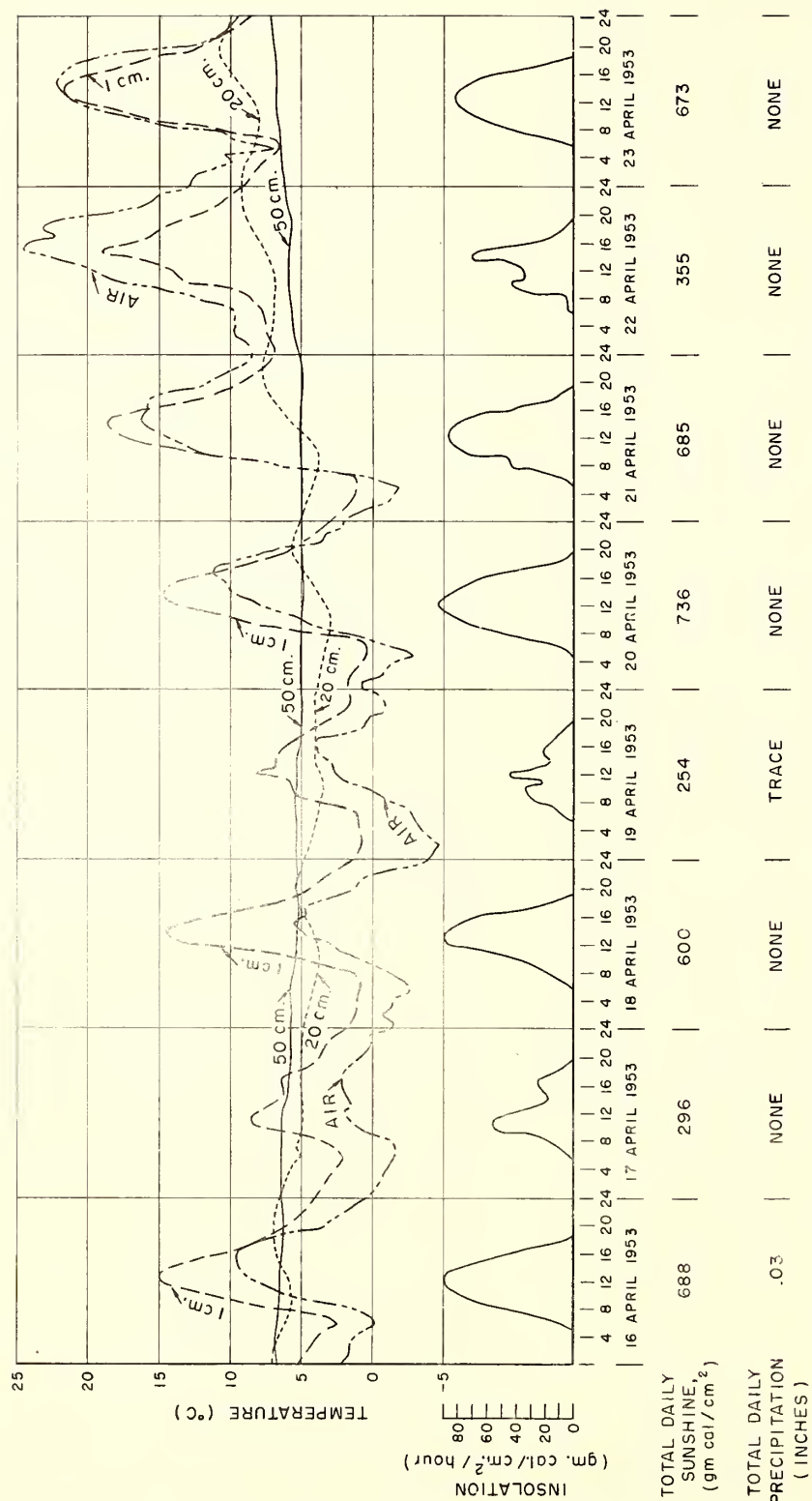
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Figure 3.--Soil temperature and air temperature during a spring period with variable sunshine at Lemont, Ill. (after Carson 1961).

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shows almost no daily fluctuation, but the warm period from April 20 to 23 caused a rise of about 2^O C. over a 72-hour period. The soil temperature at this depth reflects short-time weather patterns but is essentially independent of the daily temperature cycle.

Cold or warm rains may bring about rapid and marked changes in the temperature of surface horizons, which is part of the influence of weather. Generally the direct temperature effect of a rain is not measurable 48 hours after the rain ends.

Seasonal temperature fluctuations and soil-temperature gradients

SEASONAL FLUCTUATIONS IN THE TROPICS

Seasonal fluctuations of soil temperature are generally small in the Tropics--the zone between the Tropics of Capricorn and Cancer. Mean annual soil temperatures vary with elevation, but seasonal temperatures vary primarily with clouds and rain. The warmest seasons may be the dry seasons, for clouds and rain may outweigh the effect of the angle of the sun's rays.

We have plotted soil temperature, air temperature, rainfall, and percentage of possible sunshine for two stations (l.N.É.A.C. 1953) a little north of the Equator in the Republic of the Congo (Leopoldville). One is Nioka at an elevation of about 5,000 feet (fig. 4); the other is Yangambi at an elevation of about 1,200 feet (fig. 5). These figures show that the soil temperature is higher in "winter" than in "summer." Actually, the soil temperature fluctuates with cloud cover and rain
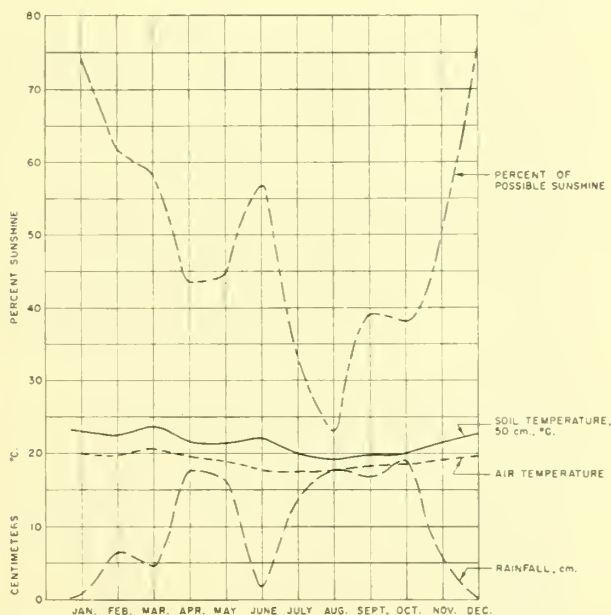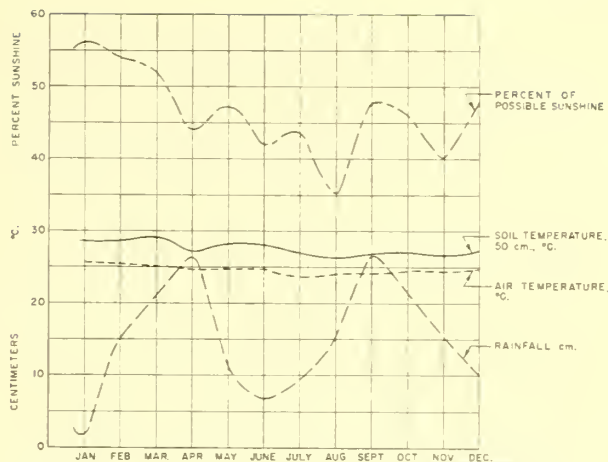

Figure 5.--Mean monthly soil temperature at 50 cm. for 1952 at Yangambi, Rep. Congo, and major climatic factors that affect it.

and appears to be most closely correlated with the amount of sunshine. In the Tropics, differences between summer and winter temperatures are small and may be in either direction. The average temperature over a 3-month season is virtually the same at all depths within the upper meter of soil.

As the temperate region is approached, near the Tropic of Cancer for example, summer soil temperatures are likely to be higher than those in winter, but the differences between the mean summer and the mean winter temperature of the upper meter of soil are usually less than 5° C. (9° F.). Tropical conditions in the United States are restricted to Hawaii and Puerto Rico.

SEASONAL FLUCTUATION AND GRADIENTS IN MID-LATITUDES

Soil temperatures in the 48 coterminous States generally show marked seasonal fluctuations. To illustrate seasonal changes under a mid-latitude continental climate such as that in much of the United States, a good record of soil temperatures from Belgrade, Yugoslavia, has been selected. The mean monthly temperatures cited by Chang (1958b) are given in table 5 and are shown graphically in figure 6. The annual cooling and heating waves extend to 12 meters (40 feet), but the amplitude of variation at this depth is only 0.1^O C. At a 14-meter depth, the temperature is constant and is the same as the mean annual soil temperature. These records show clearly that seasonal temperature fluctuations penetrate deep into the earth, well below the lower limit of soil.

The depth to the stratum with constant temperature is not the same in all soils. It is reduced by shallow ground water with its high specific heat. Records of well-water temperature in the 48 coterminous States show that in the presence of ground water the stratum of constant soil temperature occurs at about 30 feet.

Figure 4.--Mean monthly soil temperature at 50 cm. for 1952 at Nioka, Rep. Congo, and major climatic factors that affect it.

TABLE 5.--Mean monthly and annual ground temperatures at Belgrade, Yugoslavia, 1902-06[1]

Latitude: 40°48' N.   Longitude: 20°28' E.   Elevation: 139 meters
Time of observation: every hour

| Depth	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.	°C.
90 cm.-------------	5.0	4.3	6.4	9.8	14.3	17.8	20.6	21.9	20.3	16.0	11.3	7.1	12.9
1.2 m.-------------	6.9	5.8	6.8	9.2	12.7	15.8	18.4	20.0	19.3	16.3	12.6	9.1	12.8
1.5 m.-------------	7.2	6.1	6.9	9.1	12.2	15.4	17.9	19.5	19.1	16.2	12.8	9.5	12.6
2 m.-------------	9.0	7.7	7.7	9.0	11.4	14.0	16.2	17.9	18.1	16.4	13.8	11.3	12.7
3 m.-------------	11.3	10.0	9.5	9.7	10.7	12.2	13.8	15.2	16.4	16.1	14.5	12.8	12.7
4 m.-------------	12.5	11.4	10.6	10.4	10.8	11.6	12.9	14.0	14.8	15.1	14.6	13.6	12.7
5 m.-------------	12.9	12.1	11.4	11.0	11.1	11.6	12.2	13.1	13.8	14.3	14.2	13.7	12.6
8 m.-------------	13.0	12.9	12.8	12.7	12.5	12.4	12.5	12.5	12.5	12.7	12.8	12.9	12.7
10 m.-------------	12.9	12.9	12.9	12.9	12.9	12.8	12.7	12.7	12.7	12.7	12.7	12.8	12.8
12 m.-------------	12.8	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.8	12.8	12.8	12.8	12.9
14 m.-------------	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9
18 m.-------------	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
20 m.-------------	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1
24 m.-------------	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3
Air temperature[2]-----	-0.9	0.8	6.7	11.3	16.7	19.5	21.8	21.3	17.2	12.5	5.7	1.8	11.2

[1] Meteorologische Zeitschrift 1911, p. 297, in Chang (1958b).
[2] Normal mean monthly air temperature after Kendrew (1942, p. 295).
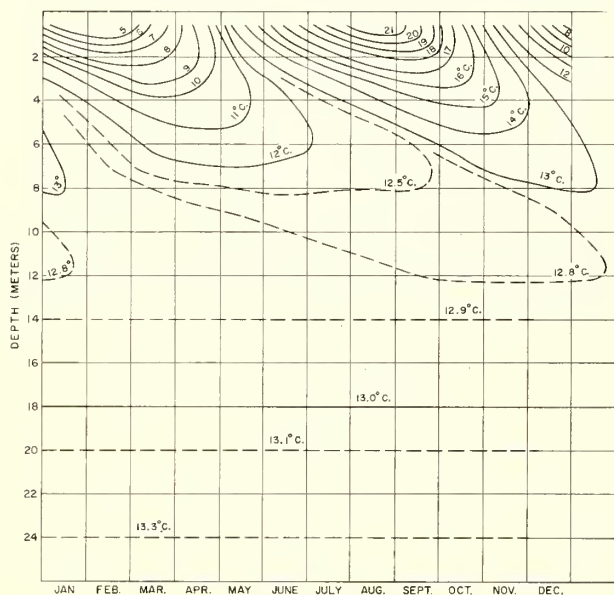
Figure 6.--Mean monthly isotherms of ground temperature at Belgrade, Yugoslavia.

Chang (1958a, p. 93) has estimated that in the absence of ground water seasonal fluctuations of soil temperature penetrate to a depth of 20 meters (66 feet) in Alaska, 15 meters (50 feet) in humid latitudes, and 10 meters (33 feet) in the Tropics. In dry soils thermal conductivity is low and, although seasonal fluctuations in temperature may be very large, the depth of penetration is not increased. At Jaipur, India (27°N. Lat.), the seasonal range in soil temperature at a depth of 20 feet was 2.7°C., but at 45 feet it was only 0.2°C. (Chang 1958b).

The amplitude of seasonal fluctuations and the months of warm and cool periods of soil temperature are primarily functions of latitude and climate. In mid-latitudes the angle of the sun's rays is most important, but clouds, rain, irrigation water, snow cover, bodies of water, direction and angle of slope, and presence or absence of shallow ground water and thick O (organic) horizons can all affect the amplitude of fluctuation. Seasonal fluctuations in mid-latitudes are generally in excess of 5°C. (9°F.). That is, the average summer soil temperature in the upper meter is more than 9°F. higher than the average winter soil temperature.

Since the temperatures of soils at high elevations tend to resemble those of soils at high latitudes, the discussion in this section is confined to soils having mean annual temperatures of 47°F. or higher. The cold soils at high elevations in the mid-latitudes are discussed with the soils of high latitudes.

Outside the Tropics soil temperature tends to decrease with depth in summer and to increase with depth in winter. In mid-latitudes the mean annual soil temperature at any given depth is very close to the average of the mean summer and winter temperatures at that depth. At a given depth in level soils the mean monthly temperature fluctuates about the mean annual temperature in an approximate sine curve.

Effect of Depth.--In a given soil the closer to the surface, the greater the amplitude of fluctuation. This relation is shown graphically in figure 7 (data from Elford and Shaw 1960). The use of long-time averages eliminates the irregularities in the temperature curves at 4 inches and 20 inches caused by the vagaries of weather.

Seasonal variations of soil temperature are greatest at the surface and decrease with depth until, at a depth of 30 feet or more, they disappear (fig. 6). The mean summer, winter, and annual soil temperatures (Chang 1958b) are plotted in figure 8 as a function of
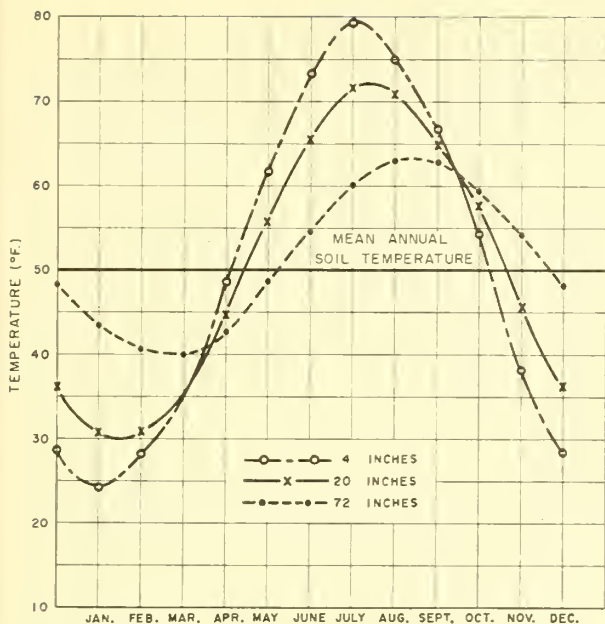
Figure 7.- Mean monthly soil-temperature curves for various depths in a soil at Ames, Iowa.
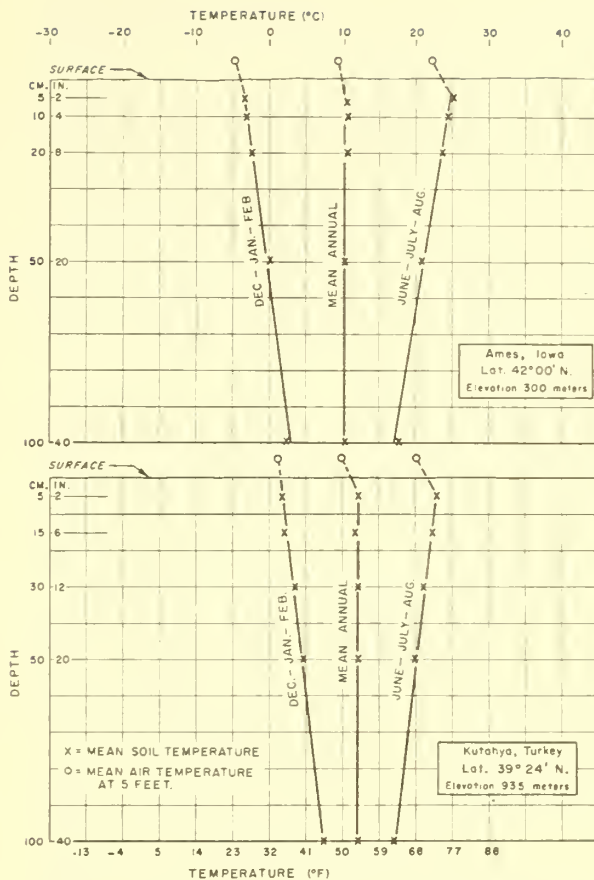

Figure 8.--Soil-temperature gradients with air temperatures for winter and summer in relation to mean annual temperatures at Ames, Iowa, and Kutahya, Turkey.

depth together with air temperatures for two stations in the mid-latitudes. If we disregard the upper inch or two, the changes with depth of the mean seasonal soil temperature are nearly linear, so nearly so that one must conclude that the mean seasonal temperature of soil to any depth within the solum is very closely approximated by the mean temperature at the midpoint in depth. The temperature gradient is positive in winter and negative in summer. It is approximately 0.6° C. per 10 cm. (1° F. per 4 inches) at Kutakya, Turkey; Odessa, U.S.S.R.; and Ames, Iowa; and 0.5° C. per 10 cm. at Fort Collins, Colo. The gradients seem very similar in most mid-latitude soils where records are available, even on undrained peats as we show later.

The graphs show that the mean summer air temperature at Ames and Kutahya exceeds the mean summer soil temperature at 50 cm. by about 1° F. Thus, the mean summer air temperature is about 1° F. higher than the average temperature of the soil to a depth of 1 meter, for the 50-cm. temperature is virtually the same as the average for the upper meter.

Mean winter soil and air temperatures do not show such a close relationship. The mean winter air temperature is 9° F. lower than the soil temperature at Ames and 7° F. lower at Kutahya. During the winter, snow insulates the soil for variable periods in mid-latitudes. The more continuous and the thicker the snow cover, the greater the difference one would predict between the mean winter air and soil temperatures.

Effect of Vegetative Cover and Irrigation.--In the humid mid-latitudes, cover can have an important influence on seasonal fluctuations of soil temperature. The differences between grass, crops, and trees in shading or insulating the soil are minor if O horizons are transient or absent.

SCS staff members measured soil temperature at monthly intervals from May to October in 1962 to compare soil temperature under forest with that in cultivated fields. The mean summer soil temperatures at 24 inches are tabulated in table 6. Conifers caused a marked reduction in summer soil temperature, whereas hardwoods had only a minor influence except at Knoxville. Table 6 shows that cultivated soils of mid-latitudes were cooler at a depth of 24 inches

TABLE 6.--Mean summer temperature at 24-inch depth in cultivated and forest soils during 1962

Location	Type of forest	Mean summer temperature			
		Air at 5 feet[1]	Soil at 24-inch depth		
			Under forest	Cultivated	Difference
		° F.	° F.	° F.	° F.
Knoxville, Tenn.-----	Hardwoods	76.2	68	77	9
Urbana, Ill.---------	Hardwoods	72.6	65	69	4
Ithaca, N.Y.---------	Conifers	66.6	58	68	10
Steele Co., Minn.----	Mixed hardwoods	67.3	57	62	5
Beltrami Co., Minn.--	Mixed hardwoods	63.5	55	58	3
Palmer, Alaska-------	Mixed conifers and hardwoods.	54.6	35	51	16

[1] U.S. Weather Bureau climatological data.

than the air at the nearest weather station. The average difference was between 1 and 2° F. for the summer. On the average soils under forest were about 9° F. cooler than the air.

Since in dry regions under natural conditions soils are partly bare or mostly bare, irrigated close-growing crops can have a very marked effect on seasonal fluctuations of soil temperature. Evaporation of irrigation water can also have a marked affect. It was pointed out earlier that data from Vauxhall, Alberta, show that an irrigated soil was 13° F. colder than the air during the summer. The mean annual soil temperature at both Vauxhall, Alberta, and Indio, Calif. (Bliss 1942), was 3° F. lower than the mean annual air temperature.

Effect of Ground Water.--Because of its large latent and specific heat, shallow ground water greatly affects seasonal fluctuations of soil temperature in mid-latitudes. The principal effects are during periods when the soil is freezing or thawing because the latent heat of freezing of water is about 80 times the specific heat.

In figure 9 we have plotted from unpublished SCS data the mean summer temperature for two soils in Steele County, Minn.--one an undrained peat and the other a cultivated Gray-Brown Podzolic soil. The undrained peat soil was about 7° F. cooler. The slope of the seasonal soil-temperature gradient is nearly the same for both soils--approximately 1° F. per 4 inches of depth. Since temperature was measured only monthly, one might question the reliability of so few observations. But the soil temperature at a depth of 2 feet or more usually changes very slowly. Moreover, we compared monthly averages of daily measure-
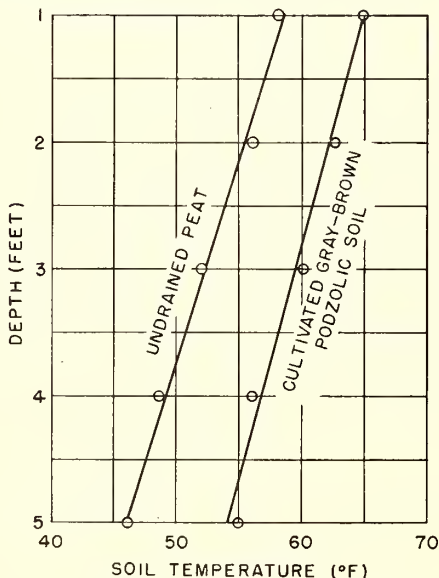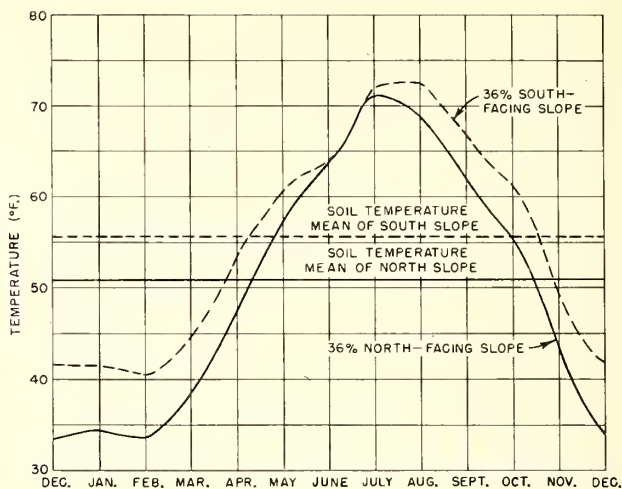

Figure 10.--Mean monthly and annual soil temperatures at a 4-inch depth on north- and south-facing slopes of Cushetunk Mountain, N.J.

ments with those made on the first day of each month at several stations and found the average error less than 2° F., an error well within the range of fluctuation caused by day-to-day weather. The straight-line relation of temperature to depth is a further indication of the probable reliability of the data.

Effect of Slope Aspect and Steepness.--The aspect (direction) and steepness of slope may affect the deviation of the mean monthly soil temperatures from the annual mean. In figure 10 we have plotted the mean monthly temperatures at a 4-cm. depth for north- and south-facing slopes of 36 percent in New Jersey reported by Cantlon (1953). The effect in winter was large compared to that in summer. The readings were made weekly with a high-low thermometer for a year, so they include not only the effects of slope and day-to-day weather but also an uncertain effect of the asymmetrical nature of the daily temperature cycle at that depth. Nevertheless, as pointed out by Cantlon, the maximum difference in the mean monthly temperatures at the two sites occurs in winter and coincides with the maximum difference in the angle of the sun's rays. Thus, the relation is probably significant. The south-facing slopes have smaller seasonal fluctuations from the annual mean than the north-facing slopes.

Figure 9.--Mean summer soil-temperature gradients for an undrained organic soil and a cultivated Gray-Brown Podzolic soil, Steele County, Minn.

TABLE 7.--Mean summer soil temperature during 1962 under various vegetative covers on north- and south-facing slopes of 20 to 30 percent

Location	Cover	Mean summer temperature at 24 inches		
		N slope	S slope	Difference
		°F.	°F.	°F.
Waterford, Calif.------	Range grass	82	87	5
Lincoln, Nebr.---------	Pasture	66	68	2
Urbana, Ill.-----------	Deciduous forest	70	72	2
Steele Co., Minn.------	Deciduous forest	63	64	1
Ithaca, N.Y.-----------	Pasture	64	68	4
Knoxville, Tenn.-------	Pasture	76	78	2

SCS staff members made measurements of soil temperature in 1962 on north- and south-facing slopes of 20 to 30 percent. The mean summer temperatures at a 24-inch depth listed in table 7 indicate differences between north- and south-facing slopes comparable to those observed in New Jersey.

SEASONAL FLUCTUATIONS IN HIGH LATITUDES

Soils in high latitudes are cold, and the seasonal soil-temperature fluctuations do not approximate a simple sine curve as those in mid-latitudes. We have plotted in figure 11 the mean monthly soil and air temperatures at Mustiala, Finland (Chang 1958b). The air temperature follows a simple sine curve and is above the mean for about 6 months of the year. The soil temperature at 50 cm., however, is above its mean only 5 months and below it for 7 months. The asymmetrical soil-temperature fluctuations reflect the combined influence of snow as an insulator during the winter and the relatively high insolation during the summer months when the sun is above the horizon all or most of the time.

In figure 12 we have plotted the mean annual seasonal soil temperature (Chang 1958b) as a function of depth for two high-latitude stations--Cape Chelyuskin, U.S.S.R., and Mustiala, Finland. The skewed seasonal fluctuations are indicated by the closeness of the winter and the mean annual temperature lines.

In these latitudes summer soil temperatures are appreciably lower than the air temperature. At Cape Chelyuskin, the mean summer air temperature is about $8°$ F. higher than the soil temperature at 50 cm. At Mustiala, Finland, the air temperature is $3°$ F. higher. The temperature gradients with depth are similar to those in mid-latitudes.

To determine whether permafrost at depth affects the temperature gradient, we also plotted the mean July soil temperature at Cape Chelyuskin. During this month the permafrost stood at about 16 inches, but the soil temperature changed as a straight-line function of depth below 4 inches.

Effect of Snow Cover.--The effect of snow cover on soil temperature at various depths (after Molga 1958)
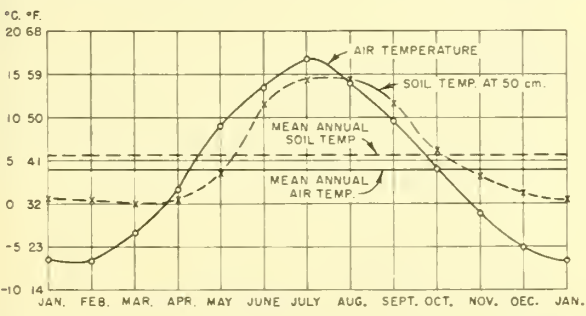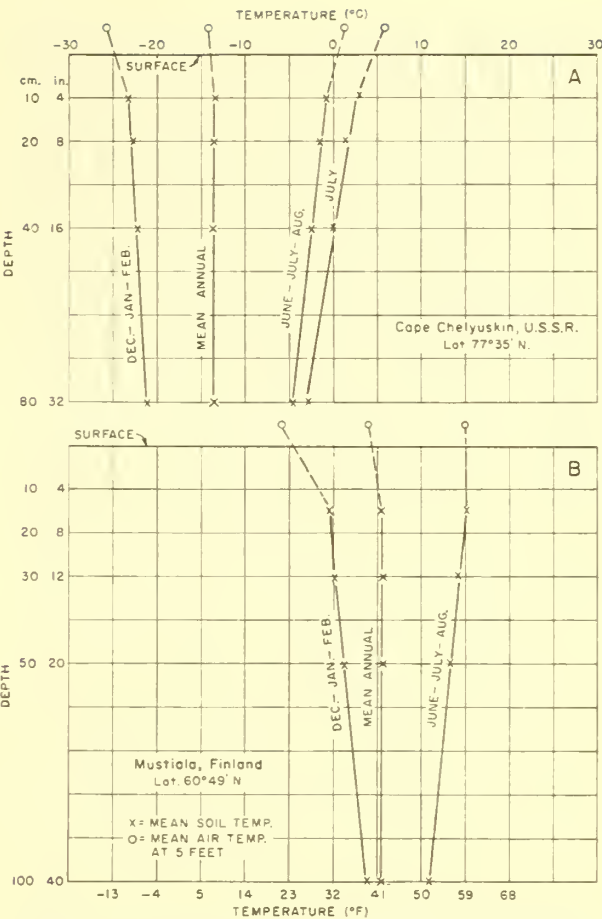

Figure 12.--Soil-temperature gradients and air temperatures for winter and summer in relation to mean annual temperatures at A, Cape Chelyuskin, U.S.S.R., and B, Mustiala, Finland.

is shown in figure 13. Here we have plotted the temperature difference between soil kept bare and soil covered with snow (bare plot minus snow-covered plot). From November through March, the snow-covered plot was warmer at all depths and the average temperature difference for the three winter months (December through February) was $4°$ C. at the 50-cm. depth. In April when air temperatures were rising and snow was melting, the bare soil warmed more rapidly and was warmer than the snow-covered plot to a depth of 40 cm.

The effect of snow on soil temperature is not limited to high latitudes and high altitudes. Snow covers are common but intermittent for the most part in mid-latitudes where mean annual soil temperatures are less than $55°$ F.

Effect of Vegetative Cover.--Covers of litter and moss commonly are thicker in the colder climates. As they thicken, they reduce seasonal fluctuations of soil temperature because they insulate the soil during the entire year. Table 6 includes two observations on the effect of cover on summer temperatures in the

Figure 11.--Mean monthly and annual soil and air temperatures at Mustiala, Finland.
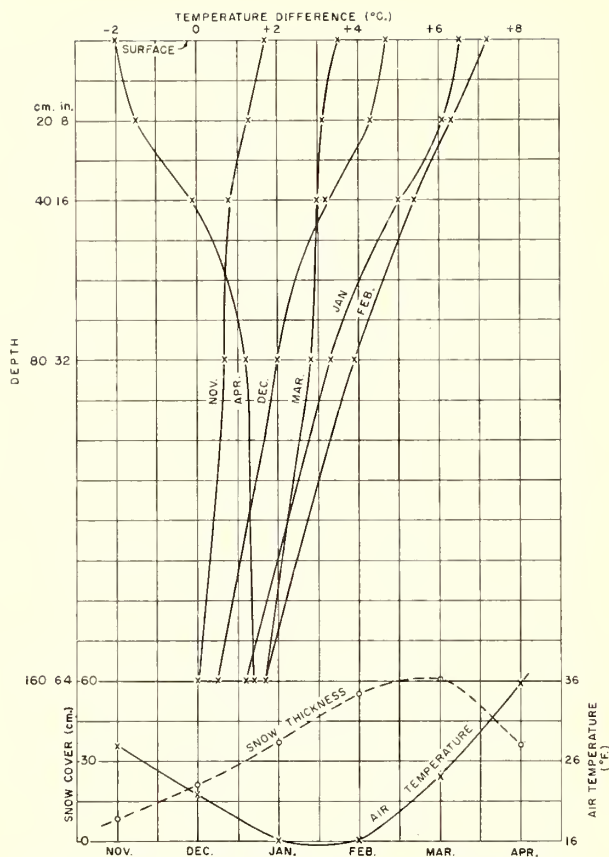
Figure 13.--Monthly soil-temperature differences between bare and snow-covered plots at Leningrad, U.S.S.R., and mean monthly air temperature and snow thickness.

colder soils--one under hardwoods and the other under mixed hardwoods and conifers. The hardwood litter had little effect in Beltrami County, Minn., but the mixed litter at Palmer, Alaska, apparently had a very large effect--a 16° F. reduction in summer soil temperature at a depth of 24 inches. A small part of this difference is due to our convention of measuring depth from the contact between the O horizon and the mineral soil. The difference would have been a little less had depth been measured from the surface of the O horizon. The mean annual air temperatures at Palmer and Beltrami County are nearly the same.

Inland in Alaska we have only fragmentary unpublished SCS data, but July temperatures of well-drained soils at a 24-inch depth at Fairbanks are about 15° to 20° F. lower under forest than under cultivation. Under much of the forest at Fairbanks there is permafrost that melts if the soils are cleared, but we cannot simply assume that removal of the forest and the O horizon has increased the mean annual temperature. The melting and retreat of permafrost could

be the result of increasing either the seasonal fluctuations or the mean annual temperature or both. No matter what other effect forest cover has, it keeps the soils cold during the summer at Fairbanks. The maximum temperature recorded at a 24-inch depth was 48° F.

Effect of Ground Water.--Because of its specific and latent heat, ground water reduces seasonal fluctuations of soil temperature. We have plotted in figure 14 the soil temperature at the 50-cm. depth for two soils at Flahult, Sweden (Chang 1958b), where mean annual soil temperatures are about 6°C. (42.8° F.).

The wet bog was warmer in winter and cooler in summer than the sandy soil. The amplitude of fluctuations in the wet bog at the 50-cm. depth was 4°C. less than in the sand.
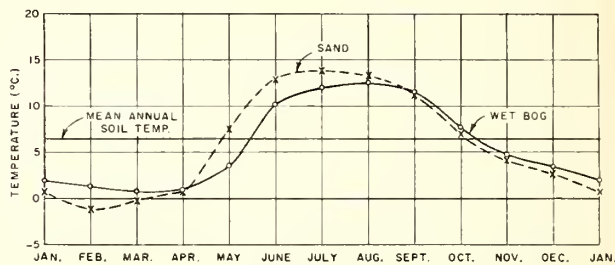

Figure 14.--Mean monthly soil temperature at 50 cm., Flahult, Sweden.

Unpublished SCS records show that in the Tanana Valley of Alaska, where mean annual soil temperatures are about 32° F., an imperfectly drained soil under forest never reached a temperature above 36° F. at the 24-inch depth in 1962. Where cleared the soil at 24 inches had a maximum temperature of over 60° F. This is, of course, the combined effect of cover and ground water.

Effect of Slope Aspect and Steepness.--Only very fragmentary data are available from high latitudes to indicate the importance of slope aspect and steepness on seasonal soil-temperature fluctuations. Measurements made during the summer of 1962 by SCS staff in the Matanuska Valley, Alaska, compared a 28-percent SW slope with a 27-percent NNW slope under grass. On June 1, the frost was 22 inches below the surface on the NNW slope and 4 feet below on the SW slope. From July 1 through September, the temperature difference was 2° F. or less at the 24-inch depth, the SW slope remaining only slightly warmer. These observations are consistent with those reported for mid-latitudes.

Measurement of Soil Temperature

From the evidence presented, it can be seen that soil temperature can often be estimated from

climatological data with a precision that is adequate for the present needs of the soil survey. If we cannot make reasonably precise estimates, we can see that the measurement of soil temperature need not be a difficult or a time-consuming task.

We have seen that for much of the United States we can estimate the mean annual soil temperature by adding 2° F. to the mean annual air temperature (table 2). We have seen that the average summer temperature of the upper 40 inches of level, well-drained, cultivated or grass-covered soils can often be approximated by subtracting 1° F. from the mean summer air temperature (fig. 8).

The mean summer temperature for a specific depth can also be estimated. To do this, we can take the average summer temperature of the upper 40 inches and correct for the temperature-depth gradient by adding or subtracting 1° F. for each 4 inches above or below 20 inches. The mean winter temperature of many mid-latitude soils can be estimated from the difference between the mean annual and the summer temperature because the differences are of the same magnitude but have opposite signs.

We have seen in figure 6 that the cooling wave at Belgrade extends to 12 meters (40 feet) and that at this depth the minimum temperature is reached about 10 months later than at 1 meter. The amplitude of variation at the 40-foot depth is less than 0.1^o C. This means that the mean annual temperature of a soil in mid-latitude can be determined at any time by a single reading at a depth of 13 meters. A single reading at a depth of 10 meters is within 0.1^o C. of the mean annual soil temperature. A single reading at a depth of 6 meters (20 feet) is within 1° C. of the mean annual temperature.

The mean annual temperature of soils underlain by deep regolith can therefore be very closely approximated at any season by using auger extensions. In some places there is an even simpler method of determining the mean annual soil temperature. Dug wells generally range from 20 to 60 feet in depth. If the water table stands between 30 and 60 feet, the well-water temperature, which is in equilibrium with the soil temperature, gives the mean annual soil temperature with an error of less than 1° C. Unfortunately, this method is suited only to humid regions where ground water is shallow and is not frozen. Extensive records of well-water temperature have shown that the water temperature between 30 and 60 feet is essentially constant throughout the year. At these depths it bears the same relation to air temperature as the soil-temperature measurements given in table 2. One precaution is necessary in using well-water temperature--the well must be in use so that water is moving into the well from the ground around.

If the soil is shallow and there are no wells, the mean annual soil temperature can be measured only over the four seasons by taking several readings at regular intervals of time. If the soil is expected to be frozen deeply at the time of one or more readings, a special thermometer can be buried or a thermocouple can be used. If the temperature of a soil is measured at a depth below the influence of the daily cycle of fluctuations, say at 20 inches, four readings equally spaced throughout the year give a very close approximation of the mean annual temperature. For example, the average of readings taken at the 50-cm. depth at Vauxhall, Alberta, on January 1, April 1, July 1, and October 1, 1962, differs from the average of two readings each day of the year by only 0.6^o F. Greater precision can be had by increasing either the number or the depth of the readings. The mean annual soil temperature computed for any 1 year will also be close to the long-term mean annual, that is, the "normal." At Ames, Iowa, for example, the standard deviation of this value for a 13-year record at the 20-inch depth is only 1° F.

Seasonal temperatures, we have seen, bear an almost linear relation to depth within the depth limits that usually concern us as soil scientists. By selecting a suitable depth and measuring the temperature on the 15th of June, July, and August, we can derive the average soil temperature for the 3-month summer period. The error will be small only if measurements are made at a depth below the daily temperature fluctuations--20 inches or more. Measurements made at a 20-inch depth give the average temperature of the upper 40 inches. A test of this method for the station at Vauxhall, Alberta, showed that the average of three daily values taken at a 50-cm. depth on June 15, July 15, and August 15, 1962, is within 1° F. of the mean summer temperature computed from daily readings.

Greater precision can be had mainly by increasing the number of readings, but readings of soil temperature should not be made at depths as shallow as 20 inches for at least 48 hours after a heavy rain.

We have also seen that the average temperature for a 3-month season varies as a linear function of depth. If we determine the mean summer temperature at several depths, say 20, 30, and 40 inches, we can estimate the mean summer temperature at any depth below the surface within the normal root zone.

Seasonal temperatures are affected by cover, slope direction and steepness, snow, ground water, rain, and clouds. Available data are inadequate to permit close estimation of the seasonal temperature of soils other than those at freely drained, cultivated or grass-covered, level sites. If we want to know more, we must make more measurements; the time required to make them is very small. The need for additional information is greatest in the colder climates because most roots cannot grow in a horizon having a temperature of 42° F. or less. The average depth of rooting is fixed by the depth having this average

temperature. We also have a general need for more information on the temperature of sloping soils to help understand the differences in adaptation of north- and south-facing slopes.

Summary

Soil temperature is a parameter important to both soil genesis and soil use. It was taken into account in older soil classification systems, and it must not be forgotten in any new systems to be used in our national cooperative soil survey.

Each horizon in a pedon has the same mean annual temperature, but the temperature is rarely the same in any two horizons at a given moment because of daily, short-term, and seasonal fluctuations. At depths below about 50 cm. soil temperature changes slowly, and at depths below about 30 feet temperature is nearly constant and is the same as the mean annual soil temperature. The mean annual soil temperature is higher than the mean annual air temperature over most of the United States. The difference is usually about 2°F. in the humid Southern and Central States, but it is more in the colder regions.

The mean annual soil temperature is largely independent of color, texture, drainage, and organic content. It is affected to a few degrees by slope steepness and direction and in some places by cover.

Seasonal fluctuations are affected by latitude, soil moisture, ground water, air movement near the ground, clouds, rain, and cover, but the effect of latitude is dominant over most of the United States. Daily fluctuations are affected by all these except latitude, but the influence of moisture and cover is dominant.

Mean annual soil temperatures and seasonal fluctuations can in general be predicted from meteorological records of air temperature, but with our present knowledge we cannot make precise estimates for many soils. We need to make more measurements of annual and seasonal soil temperatures. They do not require much time or expensive instruments. An average of four measurements a year, made at a depth of 20 inches near the 15th of the month at 3-month intervals, is very close to the mean annual soil temperature. Or a single measurement of ground- or well-water temperature at a depth between 30 and 60 feet gives the mean annual soil temperature.

The mean summer or winter temperature of the horizons of a pedon has a linear relation to depth within normal root zones. The average temperature of the upper 40 inches of soil over a 3-month season can be measured by three readings made on the 15th of each month at a depth of 20 inches. The temperature gradient with depth in mid-latitude is usually nearly 1°F. per 4 inches. It can be determined by readings at 30 and 40 inches in addition to the reading at 20 inches. Knowledge of the soil-temperature gradient permits close estimation of summer temperatures at any depth within the root zone.

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